UCRL-JRNL-209106

LAWRENCE LIVERMORE NATIONAL LABORATORY

Star Formation in High Pressure, High Energy Density Environments: Laboratory Experiments of ISM Dust Analogs

W. van Breugel, S. Bajt, J. Bradley, E. Bringa, Z. Dai, T. Felter, G. Graham, S. Kucheyev, D. Torres, A. Tielens, R. Baragiola, C. Dukes, M. Loeffler

January 20, 2005

The Dusty and Molecular Universe: A Prelude to Herschel and ALMA

Disclaimer

STAR FORMATION IN HIGH PRESSURE, HIGH ENERGY DENSITY ENVIRONMENTS: LABORATORY EXPERIMENTS OF ISM DUST ANALOGS

W. van Breugel[1], S. Bajt[1], J. Bradley[1], E. Bringa[1], Z. Dai[1], T. Felter[1], G. Graham[1], S. Kucheyev[1], D. Torres[1], A. Tielens[2], R. Baragiola[3], C. Dukes[3], and M. Loeffler[3]

[1]Lawrence Livermore National Laboratory, Livermore, CA 94551, USA
[2]SRON Laboratory for Space Research Groningen, NL-9700 AV, Groningen, The Netherlands
[3]Engineering Physics Department, University of Virginia, Charlottesville, VA 22903, USA

ABSTRACT

Dust grains control the chemistry and cooling, and thus the gravitational collapse of interstellar clouds. Energetic particles, shocks and ionizing radiation can have a profound influence on the structure, lifetime and chemical reactivity of the dust, and therefore on the star formation efficiency. This would be especially important in forming galaxies, which exhibit powerful starburst (supernovae) and AGN (active galactic nucleus) activity. How dust properties are affected in such environments may be crucial for a proper understanding of galaxy formation and evolution.

We present the results of experiments at LLNL which show that irradiation of the interstellar medium (ISM) dust analog forsterite (Mg_2SiO_4) with swift heavy ions (10 MeV Xe) and a large electronic energy deposition amorphizes its crystalline structure, without changing its chemical composition. From our data we predict that silicate grains in the ISM, even in dense and cold giant molecular clouds, can be amorphized by heavy cosmic rays (CR's). This might provide an explanation for the observed absence of crystalline dust in the ISM clouds of our Milky Way galaxy. This processing of dust by CR's would be even more important in forming galaxies and galaxies with active black holes.

Key words: Interstellar Medium; dust; star formation; galaxy formation; active black holes; cosmic rays; laboratory experiments.

1. INTRODUCTION

Although comprising only $\sim 1\%$ of the mass in the ISM, sub-micron sized dust grains control the chemistry and cooling and thus the gravitational collapse of ISM clouds in galaxies. ISM dust therefore plays a crucial role in the formation and evolution of stars and galaxies, and of planets and even life.

While star formation still occurs at the present time in dense ISM clouds of galaxies like our own, the main epoch of star formation and galaxy growth, at 10 - 1000 times the current rate, was in the early Universe at redshifts $z > 2$ or look-back times $t > 3.3$ Gyr (WMAP cosmology). During this time large bursts of star formation (starbursts) occured on galaxy wide scales, often triggered by merging of smaller, gas rich systems. At the same time supermassive black holes (SMBH's), thought to reside at the centers of galaxies, were also most active. In fact, observations strongly suggests that the formation and evolution of galaxies and SMBH's must be closely related (Magorrian et al., 1998).

UV/X-ray radiation, high velocity outflows, and energetic particles from hot stars, supernovae, gamma-ray bursts and active SMBH's all significantly affect the ISM of their parent galaxies and subsequent star formation efficiency. Indeed, energetic feedback may control galaxy and SMBH growth (Heckman 2003; Silk & Rees, 1998). Most studies of feedback mechanisms concentrate on the effects on ISM *gas* by outflows (starburst superwinds, radio jets) or ionization.

However, given the essential role that dust grains play during the star formation process, it is particularly important to examine the effects of energetic feedback on ISM *dust.* Of special interest here are highly energetic (> 1 MeV/nucleon), heavy (> Fe) CR's which have been accelerated in the shock waves of supernovae or active galaxy jets. Such particles can easily penetrate dense star forming regions (Léger, Jura & Omont, 1985) which are otherwise shielded from lower mass CR's (H, He), and harsh UV or X-ray radiation.

Processing by CR's can have profound influence on the structure (crystalline versus amorphous), lifetime (eg., destruction through sputtering), and chemical reactivity (eg., catalytic surface structure) of the dust. Direct evidence for this, from Solar flares, has been found in inter*planetary* dust grains collected in our stratosphere (Bradley et al., 1984). It is thought that similar CR bombardments of inter*stellar* dust grains may amorphize the crystalline dust that initially formed in stellar outflows. Irradiation of dust may also cause photodissociation and chemical changes in the ices of dust grain mantles and evidence for this in galaxies with active SMBH's has been found (Spoon et al., 2003).

To investigate the effects of high energy particles on ISM dust grains requires laboratory experiments. It is well known that one can discriminate two regimes for the stopping power of energetic ions (Bringa & Johnson, 2003). At keV energies the energy deposition is dominated by nuclear collisions while at MeV energies and above, corresponding to CR's, the energy deposition is due to electronic excitations. Even though heavy element (Fe) CR's are less abundant in the ISM than light elements (H, He) by a factor of $\sim 10^{-4}$ (Léger, Jura & Omont, 1985), the cumulative damage of heavy ion bombardments on ISM dust over the lifetime of ISM dust grains, $\sim 10^7$ yrs, may rival or exceed that of light ions. A number of groups have done such experiments at keV energies (e.g. Jäger et al., 2003; Mennella, Palumbo & Baratta, 2004; Demyk et al., 2004).

Since heavy CR's can easily penetrate dense molecular clouds and can sigificantly affect the structure of materials it is important to further investigate their effects on ISM dust. Furthermore, in forming (starburst) galaxies the star formation rate will be 10 - 1000 times larger than in our present day Milky Way galaxy. Since the CR fluences will roughly scale with the correspondingly larger supernova rates in these systems (e.g. Torres et al., 2004) the effects of heavy CR's on dust grains, even in the absence of active SMBH's, may be significant.

2. EXPERIMENTS AND RESULTS

To investigate the effects of heavy CR's on ISM dust analogs we have carried out irradiation experiments of forsterite single crystals using ~ 10 MeV Xe ions in the predominantly electronic stopping power regime. A full desription of our experimental setup and a detailed description of our results and analysis will be reported elsewhere. Here we simply summarize our key finding: the irradiated material shows a progressive amorphization with dose and is fully amorphized at fluences representative for those of the ISM in our own Milky Way galaxy. These results were confirmed by transmission electron microscopy (TEM) measurements of the samples and infrared spectroscopy. Energy dispersive X-ray spectroscopy (EDS) analysis of the amorphous material does not indicate any changes in chemical composition.

From these data we predict that silicate grains in the ISM, even in dense and cold giant molecular clouds, can be amorphized by heavy CR's at energies > 100 MeV. This might provide an explanation for the observed absence of crystalline dust in the ISM clouds of our Milky Way galaxy.

In future work we will attempt to also characterize the amorphization process at higher (GeV) energies and for other materialsi, and will investigate, in collaboration with other groups, differences in the formation efficiency of H_2 (the main molecular coolant in molecular clouds) as function of amorphization.

ACKNOWLEDGMENTS

The work at LLNL was performed under the auspices of the U.S. Department of Energy, National Nuclear Security Administration by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48. The work by R. Baragiola, C. Dukes and M. Loeffler at the University of Virginia was funded by the NASA Office of Space Research, Cosmochemistry Program.

REFERENCES

Bringa, E.M., Johnson, R.E., in 'Solid State Astrochemistry', p. 357-393, V. Pirronello et al. eds., Dordrecht, Kluwer (2003)

Bradley, J., Brownlee, D., Fraundorf, P., 1984, Science 226, p. 1432-14344

Demyk, K., et al., 2004, A&A, 420, 547

Heckman, T., 2003, in 'Galaxy Evolution: Theory & Observations', p. 47-55, V. Avila-Reese et al. eds., Revista Mexicana de Astronomia y Astrofisica (Serie de Conferencias) Vol. 17, (2003)

Jäger, C., et al., 2003, A&A, 401, 57

Léger, A., Jura, M., & Omont, A., 1985, A&A, 144, 147

Magorrian, J. et al., 1998, AJ 115, 2321

Mennella, V., Palumbo, M., Baratta, G., 2004, ApJ, 615, 1073

Silk, J., and Rees, M., 1998, A&A, 331, L1

Spoon, H., et al., 2003, A&A, 402, 499

Torres, D., Reimer, O., Domingo-Santamaria, E., Digel, S., 2004, ApJ, 601, L75